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DECENTRALIZED COORDINATED CONTROL STRATEGY OF ISLANDED MICROGRIDS

by

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AALBORG UNIVERSITY
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Dissertation submitted to Faculty of Engineering, Science
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ENGLISH SUMMARY

Facing the challenges brought by the traditional large power system concerning the environmental and economic issues, along recent years distributed generation is considered as an alternative solution to provide clean energy in a local manner. In this context, Microgrid which performing as a local small size grid, is emerging as a promising concept to flexibly control both sides of power generation and consumption as an integral controllable unit. Regarding whether there is main grid participating in the power regulation, the operation of Microgrid can be mainly classified as two modes: grid-connected mode and islanded mode. In the islanded mode operation, since there is no energy back-up from the main grid, the coordinated control of power balance between generation and consumption encounters more challenges and this thesis is mainly focused on this scope.

Hierarchical structure can be applied on the control of Microgrid which analogic compared with the conventional frequency regulation of large power system. This thesis starts from the investigation of a coherent primary control level that can be generally implemented on distributed units to achieve global active/ reactive power distribution, as well as grid voltage/frequency regulation. In order to enhance the reliability of overall islanded Microgrid operation, basic functions of coordinated control which taking into account the state of charge (SoC) limitation and power availability of renewable energy sources is implemented in a distributed level without additional communication facility assistance within this thesis. Here two bus-signaling method (BSM) methods are proposed. The power line is then not only taken as physical connection among the distributed units, but also the signal carrier to inform Microgrid components changing their control actions. Moreover, this BSM control principle is applied on both AC and DC islanded Microgrids which utilizing bus frequency and bus voltage as signaling variables respectively.

Apart from the primary coordinated control, the distributed secondary control is introduced on the top of the coordinated control strategies in this thesis, in order to

promote the decentralization of the overall system. Especially the consensus algorithm based secondary level is investigated in the thesis in order to simplify the communication configuration which only flood information through the neighboring units. The detailed developing steps for this distributed secondary control based on consensus algorithm are introduced in this thesis.

Keywords: Microgrids, coordinated control, bus-signaling, primary control, distributed secondary control, renewable energy control strategy, reactive power distribution, frequency regulation, voltage regulation.

DANSK RESUME

Her skrives det danske resume. Du kan eventuelt læse 'Facing de udfordringer, som det traditionelle store elsystem vedrørende de miljømæssige og økonomiske spørgsmål, langs de seneste år decentral produktion betragtes som en alternativ løsning til at levere ren energi i en lokal måde. I denne sammenhæng Microgrid der udfører som en lokal lille størrelse nettet, fremstår som en lovende koncept til fleksibelt at styre begge sider af elproduktion og forbrug som en integreret kontrollerbar enhed. Om, hvorvidt der er vigtigste gitter deltager i effektregulering, kan driften af Microgrid hovedsageligt klassificeret som to tilstande: nettilsluttet mode og islanded mode. I islanded mode operation, da der ikke er energi inert back-up fra de vigtigste nettet, koordineret styring af magtbalancen mellem produktion og forbrug møder flere udfordringer, og denne afhandling er hovedsageligt fokuseret på dette anvendelsesområde.

Hierarkisk kontrolstruktur kan anvendes om kontrol med Microgrid som analog sammenlignet med den konventionelle frekvens regulering af store elsystemet. Denne afhandling starter fra undersøgelsen af et sammenhængende primære kontrol niveau, der kan generelt gennemføres på distribuerede enheder til at opnå global aktiv og reaktiv effekt distribution. For at øge pålideligheden af den samlede islanded Microgrid drift grundlæggende funktioner i en koordineret kontrol, som tager hensyn til ladetilstand (SoC) begrænsning og magt tilgængeligheden af vedvarende energikilder gennemføres på en distribueret niveau uden yderligere kommunikation assistance inden for denne afhandling. Her foreslås to bus-signalering metode (BSM) metoder. Den højspændingsledning derefter ikke kun tages som fysisk forbindelse mellem de forskellige enheder, men også det signal luftfartsselskab at informere Microgrid komponenter skiftende deres kontrolaktioner. Desuden er dette BSM kontrol princip anvendes på både AC og DC islanded Microgrids som udnytter bus frekvens og bus spænding som signalering variabler.

Bortset fra den primære koordineret kontrol, er det distribuerede fornyet kontrol indført på toppen af de koordinerede bekæmpelsesstrategier i denne afhandling for at fremme decentralisering af det samlede system. Især konsensus algoritme baseret sekundært niveau undersøges i afhandlingen for at forenkle kommunikationen konfiguration, som kun udveksle oplysninger gennem de omkringliggende enheder. Introduceres de detaljerede udviklingslande trin for dette distribueret fornyet kontrol baseret på konsensus algoritme.

Nøgleord: Microgrids, koordineret kontrol, bus-signalering, primær kontrol, fordelt sekundær kontrol, kontrol af vedvarende energi, reaktiv magt distribution, frekvens regulering, spændingsregulering.

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- D. Wu, F. Tang, T. Dragicevic, J. C. Vasquez, and J. M. Guerrero, “Autonomous Active Power Control for Islanded AC Microgrids With Photovoltaic Generation and Energy Storage System”, *IEEE Transactions on Energy Conversions*, vol. 29, no. 4, pp. 882–892, Dec. 2014.
- D. Wu, F. Tang, T. Dragicevic, J. M. Guerrero, and J. C. Vasquez, “Coordinated Control Based on Bus-Signaling and Virtual Inertia for Islanded DC Microgrids”, *IEEE Transactions on Smart Grid*, vol. PP, no. 99, pp. 1–1, 2015.

Publications in Proceedings with Peer Review

- D. Wu, F. Tang, J. M. Guerrero, J. C. Vasquez, G. Chen, and L. Sun, “Autonomous Active and Reactive Power Distribution Strategy in Islanded Microgrids”, in Proc. of 2014 IEEE Applied Power Electronics Conference and Exposition (APEC 2014), pp. 2126–2131, 2014.
- D. Wu, T. Dragicevic, J. C. Vasquez, J. M. Guerrero, and Y. Guan, “Secondary coordinated control of islanded microgrids based on consensus algorithms”, in Proc. of 2014 IEEE Energy Conversion Congress and Exposition (ECCE), 2014, pp. 4290–4297.

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This present report combined with the above listed scientific papers has been submitted for assessment in partial fulfilment of the PhD degree. The scientific papers are not included in this version due to copyright issues. Detailed publication information is provided above and the interested reader is referred to the original published papers. As part of the assessment, co-author statements have been made available to the assessment committee and are also available at the Faculty of Engineering and Science, Aalborg University.

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Dan Wu

Aalborg, 24 June 2015

TABLE OF CONTENTS

Chapter 1	Introduction	13
1.1	Background and Concept of Microgrid	13
1.2	Microgrid Control Strategies – Hierarchical Control From Modular Level to System Level	16
1.2.1	Control Modes of Converter Based Elements.....	17
1.2.2	Primary Control Strategy with Droop Control and Reverse DroopMethods	19
1.2.3	Two Links to Configurate Microgrid Elements – Power Line and External Communication	20
1.3	Coordinated Control Strategies in Microgrids.....	22
1.3.1	Coordinated Control Functions for islanded operation	22
1.3.2	Coordinated Control with Bus-signaling Method.....	24
1.3.3	Decentralized Hierarchical Coordinated Control.....	26
1.4	Motivation of the Work	28
1.5	Thesis Contribution	31
1.6	Thesis Objectives.....	33
1.7	Thesis Outline.....	34
Chapter 2	Paper 1	36
Chapter 3	Paper 2	37
Chapter 4	Paper 3	38
Chapter 5	Paper 4	39
Chapter 6	Paper 5	40
Chapter 7	Concluding Remarks	41
7.1	Summary	41
7.2	Contributions	43
7.3	Future Work	44
Bibliography		45

CHAPTER 1 INTRODUCTION

1.1 BACKGROUND AND CONCEPT OF MICROGRID

The increasing demand of energy consumption and raising environmental pressure on the traditional concentrated power generation based on fossil fuel, coal and nuclear, is cherishing a near future of deploying cleaner and more efficient energy exploit ways. Although the manner of utilizing clean energy varies, the society and research has been gradually to embrace the new form of power generation that utilizes the graphically dispersed and clean generator – distributed generation (DG) [1], [2]. Compared to the conventional top-down electricity infrastructure, the DG utilizes locally installed and relatively small capacity electrical generation, which can include renewable energy resources for example of solar and wind energy [3]–[5], small hydro power [6], [7] and biomass [8], [9] etc., and also can comprise some non-renewable sources such as small size gas and diesel turbines [10], [11]. Therefore, the DG not necessary refers to employ complete renewable energy source. Rather, it indicates a system structure that the downstream or end of power system utility not only passively act as power consumer, but also actively take the role as power producer. The DG facility brings the advantages such as [12]–[14] i) flexibly utilization of the downstream locally installed energy sources (especially renewable energy sources), ii) convenient storing energy in a dispersed way and thus can be realized in a lower scaled capacity, iii) can be used to perform peak-shaving action in terms of economic benefits.

This end-to-end manner of power generation and consumption, similar with the internet structure, naturally brings the promise of smart grid (SG) round the corner together with the advanced communication technology [15], [16]. However, due to the inherent limitation and strict requirement of power system, the massive application of DG facility raises the following challenge [17]–[19]: i) The power

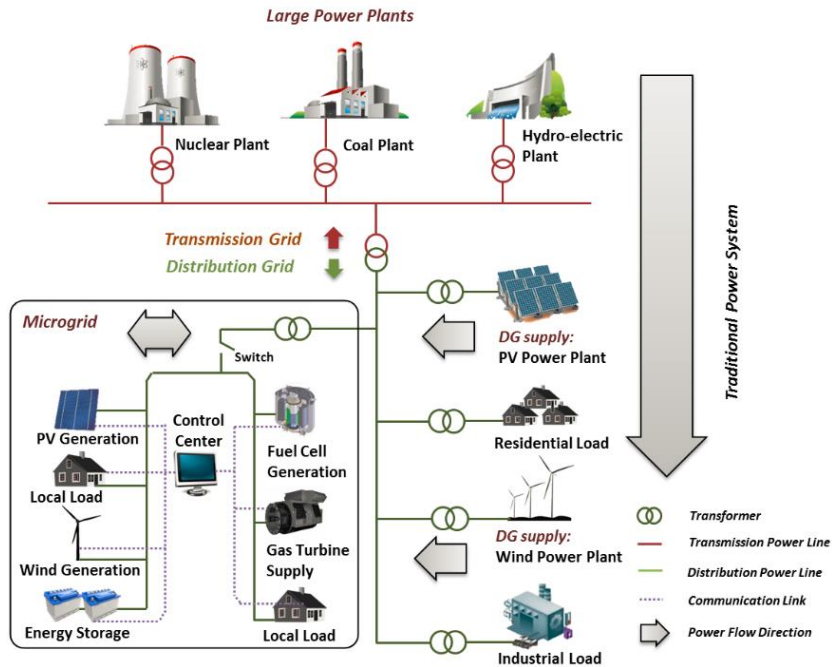


Figure 1-1 System scheme integrated by traditional power generation, DG facility and Microgrid paradigm.

electronic device interfaced DG units usually does not contribute to the frequency inertia, thus their plug-and-play characteristic when the electrical faults happen can introduce the frequency instability to upstream power system. ii) The change from traditional unidirectional to bidirectional power flow of these casually located DG units takes the difficulty of power dispatch and device protection. iii) The large amount of dispersed power electronic equipment and passive components bring new power quality issue that harmonic can penetrate among the network. Therefore, in order to maintain the merit of flexibly utilization of these distributed resources, and to alleviate the potential harm to the traditional power system by totally dispersed DG infrastructure, researchers are seeking new ways that can form these DG units into a smaller size of grid which can sustain the power consumption by itself, and at the same time is able to interact with other small grids and upstream grid, by means of energy management systems. Hence the concept of Microgrid is proposed and widely investigated in recent years [20]–[23]. Fig.1-1 shows a simple

system schematic integrated by traditional power generation paradigm, DG facility and Microgrid concept.

Microgrid groups the DG units together with distributed storage (DS) system, local (electrical and/or thermal) loads usually comprises two modes of operation: islanded mode and grid-connected mode [24]. In general, the Microgrid has only one point of common coupling (PCC) to the external system. Therefore, instead of using massive and various grid-connected interfaces of DG units, the Microgrid can be considered as an integration of these DG units, and acts as a controllable cell to import/export power from the view point of host main grid [25]. Compared to the DG facility, Microgrid has potential to optimize utilization of DG units by complementing the advantage of different DG sources, and meanwhile reduce the risk of fault when connecting dispersed DG units to the main grid separately. Furthermore, when there is an occurrence of fault on the host main power system, the PCC is disconnected so that the Microgrid operates as an autonomous system to sustain the power balance between generation and consumption by itself [26], [27]. This environment of power balance is achieved by means of energy management system (EMS) and designing proper control strategies among DG, DS and local loads [28]–[31]. Due to this convenient power supply manner which can be exempt from being interacted with main grid electrical status, the islanded Microgrid operation is becoming a mainstream for the remote onsite microgrid projects nowadays [32]–[34].

In these islanded Microgrid applications such as avionic, marine and rural areas, the AC microgrids are still presently dominant due to the intrinsic characteristic of traditional distribution system [35]–[37]. However, with the proliferation of photovoltaic (PV) generation, and raising attractiveness of some nature DC source power supply such as fuel cells, the DC Microgrids witness fast growth in recent years [38], [39]. Besides reducing power conversion stages, DC grids also bring the advantages as simplifying complex control strategies used for synchronization, power quality issues taken by AC grids [24], [35]. As well as the circuits of modern electrical equipment requires nature DC power supply, the application of DC

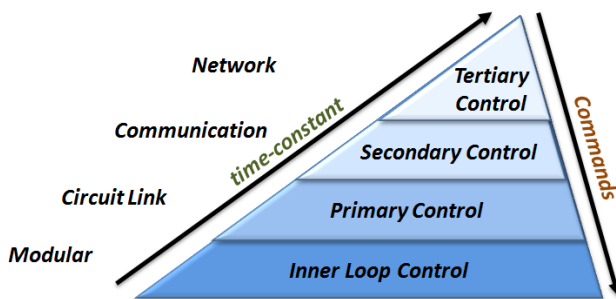


Figure 1-2 Hierarchical control structure with four layers.

Microgrids can be seen in the scenarios such as charging plug-in hybrid electric vehicles [40], [41], datacom centers [42] and future building electrical systems [43].

1.2 MICROGRID CONTROL STRATEGIES – HIERARCHICAL CONTROL FROM MODULAR LEVEL TO SYSTEM LEVEL

Hierarchical control strategy is proposed in order to make the control objective of Microgrids in a clear and systematic way, as shown in Fig. 1-2 [23], [44], [45]. With power electronic interfaced DG units, the bottom level refers to the inner loop control. It considers the basic control strategies for each single component of DG units and does not take into account the interaction of other Microgrid unit. With idealizing of inner loop regulation performance, the primary loop can ignore the inner loop time-constant which means the feedback of inner loop can track the commands from primary level in a perfect way [46], [47]. The control objective of primary level is to distribute power among DG units and regulate bus voltage and frequency, by considering circuit connection among elements [44]. So the separate modular control at bottom inner loop is linked with physical circuit at primary level. Similarly, the regulation of primary loop can be idealized when designing secondary control. With this secondary control, the Microgrid system is linked and modeled by communication scheme [48], [49]. The objective of secondary control is to adopt specific communication configuration to adjust the global system variables. For example it can be used to restore the bus voltage/frequency and adjust reactive power sharing accuracy. Finally, the tertiary level on the top of the

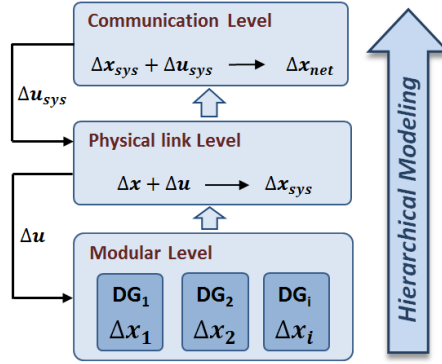


Figure 1- 3 Evolution process of modeling hierarchical control.

hierarchical control is managed to deal with long-term network assignment (power prediction, dispatch etc.) [50]–[52]. The idealization with the previous assumption can be realized by employing low-pass-filters which separate the bandwidth between two different loops. And it can be seen from Fig. 1-2 that the time-constants of different loops are increased from bottom to top level, and control commands are sending back as a reverse way in the hierarchical control structure [23]. Fig. 1-3 shows a more detailed evolution process of hierarchical control. At the bottom level, each DG unit operates separately as a single cell which has its own state variable Δx_i and passively receives the input variable Δu_i . Then these different cells form into an interactive system considering physical link at primary level, which integrates the inputs with states to new state variable Δx_{sys} . In a further step, the secondary control integrates the primary system variable and input Δu_{sys} to a more comprehensive state Δx_{sys} , by taking into account the communication scheme. With the state variables increasing to describe a more comprehensive system behavior, it can be seen that this hierarchical control leads to an evolution process from component level to system level in Microgrids [53], [54].

1.2.1 CONTROL MODES OF CONVERTER BASED ELEMENTS

The basic inner loop level defines two kinds of control modes with power electronic interfaced element: voltage control mode (VCM) and current control

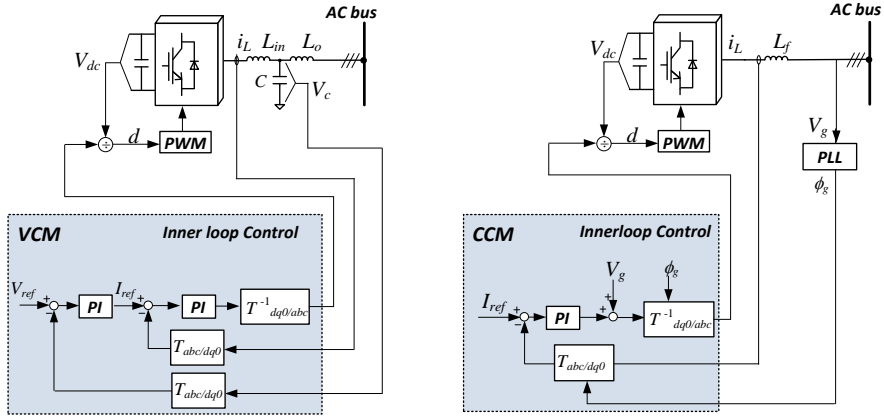


Figure 1-4 Inner loop control structure of VCM and CCM units.

mode (CCM). According to different control objectives, power electronic interfaced DG units can be classified into grid-forming units and grid-following units [52]. The grid-forming units are usually controlled in VCM to regulate the grid frequency and voltage, so that to “form” grid. And the grid -following units are controlled in CCM to generate active and reactive power based on the synchronized phase from grid. The power generated by CCM units can be followed with the maximum power point (MPP) decided by the environment condition, which is usually implemented by renewable energy sources (RES) [55], [56]. And VCM units are often employed by the energy storage system (ESS) units or the sources can provide enough power reserve so that to act as energy buffer between the power generation from RES and load consumption [57]–[59]. The control modes of VCM and CCM are classified by the control structure of inner loop, which is shown in Fig. 1-4 with a three phase system controlled under d - q reference frame for example. Based on this basic structure of VCM and CCM inner loop, advanced control strategy (e.g. harmonic and/or unbalance compensation) can be realized by adding or modifying inner loop controllers [57], [58], [60].

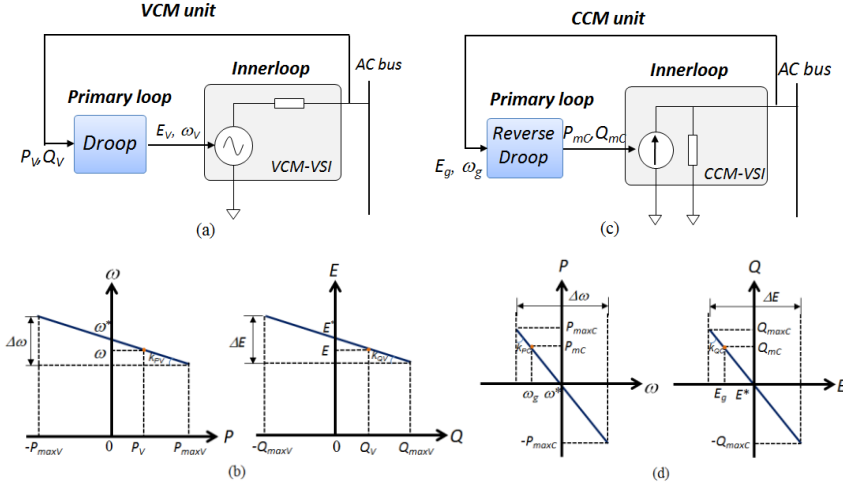


Figure 1-5 Primary control level of VCM unit (a) with droop control(b), and CCM unit (c) and reverse droop control (d).

1.2.2 PRIMARY CONTROL STRATEGY WITH DROOP CONTROL AND REVERSE DROOP METHODS

With only ideal inner loop control the islanded Microgrid system is hard to get capability to manage power among DG units in a distributed way since the converters have no inertia compared to conventional synchronous generators. For example, the VCM unit can keep the bus frequency and voltage at stable value but passively regulate the output power. This inherent property leads to the uncontrollable power distribution when multiple VCM units with only inner control loops connected together. In contrast, CCM units are able to regulate the output power but have little contribution to the regulation of the bus frequency and voltage.

In this context, droop control is proposed in order to achieve autonomous power distribution among VCM units [61]–[64]. Without droop controller, the VCM under inner loop shown in Fig. 1-4 can be simplified as Thevenin circuit as shown in the scheme of Fig. 1-5(a). In this case there is no damping action for the ω/E in terms of P/Q . Then with droop controller on the top of inner loop, the VCM units

sacrifice the output frequency and voltage regulation performance to achieve power sharing capability with managing of droop slopes (Fig. 1-5(b)). With respect to CCM units with inner loop shown in Fig. 1-4, it can be equivalent to a Norton circuit. The droop control strategy cannot be implemented directly since the outputs of droop control are voltage amplitude and frequency. Therefore it is naturally to extend a dual primary level controller for CCM compared to the droop controlled VCM units. The principle of reverse droop is similar to a contrary operation of droop method (Fig. 1-5(c)). With only ideal control of inner loop for CCM units, there is no damping action for the P/Q in terms of ω/E . Then by adding primary reverse droop control, the CCM units are able to participate in the regulation of bus frequency and voltage together with VCM units (Fig. 1-5(d)). It can be seen that this primary level makes the control objectives of VCM and CCM units more flexible, and even can be exchanged. Moreover, instead of sending specific power reference to CCM units, the power distribution is realized at primary level by conveniently assigning those droop and reverse droop coefficients proportionally. Therefore all these DG units are able to share active and reactive power together in a coordinated and unified way.

1.2.3 TWO LINKS TO CONFIGURATE MICROGRID ELEMENTS – POWER LINE AND EXTERNAL COMMUNICATION

With inner loop and primary loop control strategies, each converter interfaced component can be treated as a black box with specific input control signals and corresponding output signals as power, frequency and voltage. Then the Microgrids bring up to the system level which considers interaction among these components. In the system view point, there are two links to connect all DG, DS and local loads together inside the Microgrids, as shown in Fig. 1-1. The first link is power line, which is electrical line that inherent link Microgrid elements together no matter if there is advanced control strategies to manage output power of each component. And this link of power line ensures the power flow relation inside the network satisfies the Kirchhoff Circuit Laws. On occasions that protection action change the

system configuration, the power line connection can be dynamically switched based on the current electrical scheme.

Another channel that links Microgrid components together is communication line. The communication channel is not a must to ensure the system basic operation, and it can be utilized as a channel to achieve the advanced functions in Microgrids that needs for exchanging information of each other. A variety of communication infrastructure can be used for Microgrids as Internet, Ethernet, Wifi, WiMax [65], [66], and the network architecture is constructed based on seven layer OSI model [67]. The Microgrids with this external communication link usually has a Microgrid Central Controller (MGCC) to process those data collected by the distributed units through communication. The main function of MGCC is to coordinate DG, DS, and local loads in a reliable and optimal way, for example to manage power generation of DG units and load consumption in terms of economical view point [52]. After making decision, the MGCC sends back the control signal to local controllers, and those distributed units follows the commands to adjust the output power or voltage and frequency.

It can be seen that both links hold the characteristic that share data carried on its channel. Then the coordinated performance of Microgrids can be achieved based on these two links in a hierarchical way. This indicates the basic functions to coordinate different units can be implemented by using power line channel. Droop/reverse control of primary level can be then considered as an example which regulating the power line variables to achieve power distribution. Other technologies that using power line for coordination can be seen as power line communication (PLC), which injects a range of high frequency components over AC or DC power lines as communication signals to achieve power management among converters [68]. Bus-signaling method (BSM), which using different thresholds of power line variables to control power generation and demand side management is attracting a lot of attention in recent years [69]. The fundamental functions as the power curtailment and load shedding can be realized by using those power line technologies. Then in terms of the communication link, other advanced

objectives of Microgrid operation like the optimization and long term power scheduling can be implemented as additional or auxiliary functions which rely on complex algorithms.

1.3 COORDINATED CONTROL STRATEGIES IN MICROGRIDS

The definition of coordinated control strategy in Microgrids is very extensive based on its applications. For example, according to the operation modes of Microgrids it can be classified as grid-connected or islanded coordinated control when there is or no main utility grid participated in the power regulation [70]. And with respect to the power distribution, it can be used for active power distribution, reactive power sharing, and harmonic compensation and sharing performance based on different capacity of distributed units. It also can be classified considering different of distributed units' properties. For example there are coordinated control strategies among multiple DGs proposed considering the power generation capacity [71], [72], and also the control strategies among DSs for power sharing [70], [57], as well as the coordination between DG, DS considering environment and state of charge (SoC) conditions [73], [74]. In general, it can be referred to the power management among those distributed units taking into account specific control objectives. And the characteristic of coordinated control is that each unit is then not independently controlled, but considered the limitations of other units to globally achieve a reliable and optimized regulation performance.

1.3.1 COORDINATED CONTROL FUNCTIONS FOR ISLANDED OPERATION

Among those control objectives of the coordinated performance, the coordinated control strategy can be generalized as: i) fundamental coordinated control, and ii) advanced coordinated control. The fundamental coordinated control in islanded Microgrids has the following characteristic,

- properly keep the power balance between the generation and consumption
- perform a stable bus frequency and voltage regulation
- obtain a safe operation considering each unit capacity without create damages on the equipment
- necessary for islanded Microgrid operation with multiple units

For example, in terms of islanded Microgrids with ESS and RES units, the ESS plays an important role for achieving the goal of power balance and grid frequency support in a safe range of state of charge (SoC). In the moderate range of SoC, ESS and RES units are usually controlled in VCM and CCM units respectively. However, this simple active power regulation strategy will lead SoC out of safe region if imbalance between consumption and generation lasts long enough. When the RES units continuously generating excess power than the load consumption, SoC of ESS can be too high and eventually leads to overcharge condition. Similarly, when the demand side keeps consuming power at high level and larger than the RES generation, over discharged situation can happen as a result. And it is well known that these situations may bring permanent damage to the ESS. On the other hand, strict active power regulation of the ESS to maintain it within the safe SoC limits while ignoring the imbalance of power generation and consumption will deteriorate the frequency regulation function [75]. Hence, the fundamental coordinated power control strategy in this case is necessary to be implemented considering status of all microgrid elements such as the SoC of ESS, power available from the RES, and power demand of loads.

The advanced functions of coordinated control for islanded Microgrids can include the following characteristics,

- perform optimization for the power distribution among considering generation cost, revenue, fuel consumption etc.
- strict regulation of bus frequency and voltage at specific values on occasions as synchronization with main grid is in need.

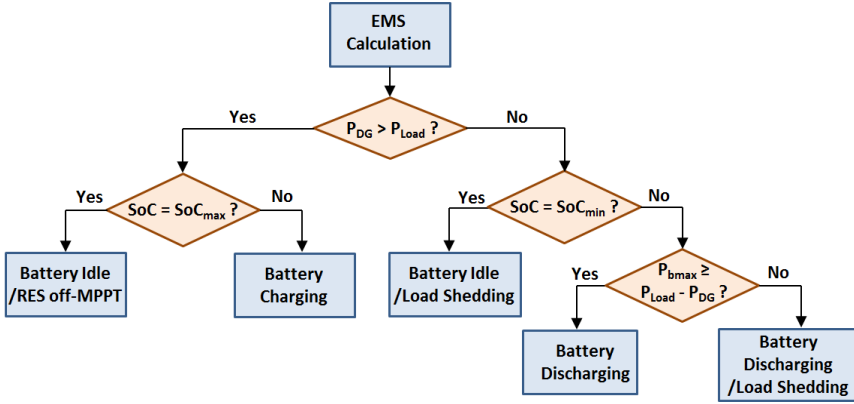


Figure 1-6 Coordinated operation principle based on EMS decision [91].

- compatible with fundamental coordinated control, and is not a must function for islanded Microgrid operation.

The advanced coordinated function usually needs communication channel to assist the performance. For example, secondary control to restore the bus frequency and voltage amplitude can be taken as an example belongs to advanced functions of islanded Microgrids.

1.3.2 COORDINATED CONTROL WITH BUS-SIGNALING METHOD

In order to achieve the aforementioned coordinated function of islanded Microgrid, usually centralized control based on EMS is implemented [73], as shown in Fig. 1-6. It can be seen that the control actions are performed based on the information collected as: power delivered from generation, storage and consumption units, as well the SoC conditions of ESS. On one hand, when the SoC is beyond the maximum value, battery should be switched to idle mode, and RES units changed to off-MPPT mode. On the other hand, when the SoC is lower than the minimum value, the battery is also switched to idle mode and central controller sends out commands to load relays to enable load shedding actions. This centralized control algorithm for coordinated performance relies on EMS for collecting and

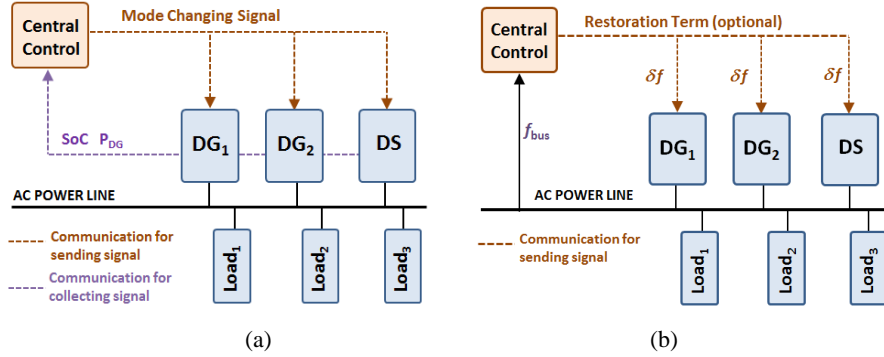


Figure 1-7 Coordinated control structure based on EMS (a) and BSM (b).

sending out commands to distributed units through communication link, as shown in Fig. 1-7(a) (Here an AC islanded Microgrid is taken as an example).

As mentioned in Section 1.2.3, there are two links to configure the Microgrid elements. Besides the communication link, there is also power line inherently connecting all the components together. Therefore it is naturally come to utilize power line variables (frequency/voltage) as carrier to inform each other status and thus realize the coordinated performance. And this is the basic motivation BSM. According to the approaches that how BSM change the power line variables, we have:

1) Passive method. In this way one distributed unit (normally the ESS unit) firstly changes the control mode, and then the power line variables changing passively as a reaction of the power unbalance between the generation and consumption. When receiving this bus frequency/voltage changing signal, other units change their control modes as a result to keep the net power balance.

2) Active method. In this way the power line variable is changed directly by the active unit, and to inform other units change power contribution or control modes. This active method can be compared similarly with the PLC that actively injecting a series of specific bandwidth signals into the power line. Meanwhile BSM realizes this signaling action by continuously changing the bus frequency/voltage values with grid forming unit.

By implementing the BSM, the basic functions of coordinated performance can be realized in a distributed way even without the interference of central controller. Therefore it can be employed in simpler and smaller size of Microgrid systems where the advanced functions of system are not requisite, in this sense the overall investment of system can be reduced, for instance the expense on communication equipment can be exempted. Even for some circumstances of Microgrid facility that both fundamental and advanced functions are necessary as mentioned in the previous section, BSM based Microgrid still hold several benefits. Take Fig. 1-7(b) for example, the fundamental coordinated performance is ensured by using BSM with power line, and the advanced functions (e.g. bus frequency restoration) are additionally achieved with central controller. In this way, the different functions are implemented in a hierarchical way. For one thing this means the data processing burden in central controller for energy management is able to be reduced, and more space can be used for the additional complex algorithm for advanced system functions (e.g. market bid, power/energy prediction). For another thing the amount of data that needs to be carried by the communication link is also reduced as shown in Fig. 1-7(b). Based on this hierarchical structure, the islanded Microgrid is able to operate autonomously even when there is unexpected fault on the communication link which leads to the improvement on overall system reliability.

1.3.3 DECENTRALIZED HIERARCHICAL COORDINATED CONTROL

As illustrated in 1.3.2, the BSM based coordinated control is able to perform the primary action in a distributed way. However as shown in Fig. 1-7(b), its distributed property is deteriorated with the central controller for the action of secondary performance. Therefore it comes to consider that using decentralized secondary control structure toward promoting the decentralized hierarchical coordinated control.

Fig. 1-8 shows an example of system diagram using central and decentralized secondary control respectively. For Fig. 1-8(a), there is only one secondary

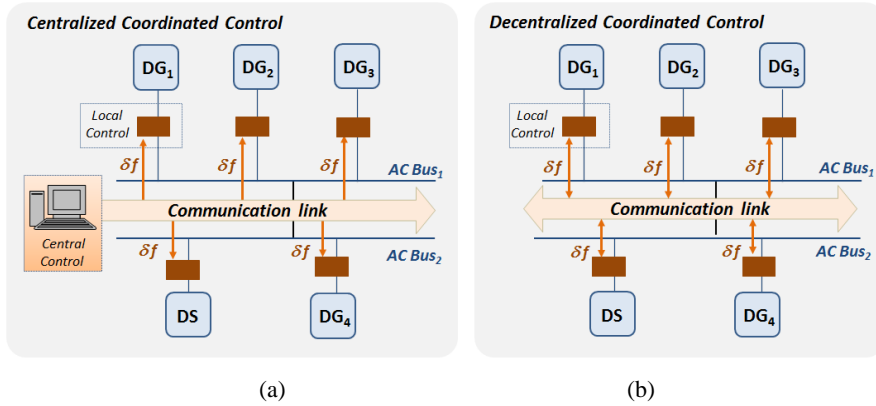


Figure 1-8 Coordinated control with central (a) and decentralized secondary control (b).

controller and it is located in the central control algorithm. The central controller sends out the unified frequency adjust term to the distributed primary coordinated controller. This algorithm is simple to implement but has single-point-failure at the point of central control output. With respect to decentralized structure as Fig. 1-8(b), the secondary algorithm is implemented in each of the local controller of distributed units. And each secondary controller generates its own adjust term to the primary coordinated control. Since all the distributed units need to be synchronized for the restoration performance, the adjust term is thereby an average outcome by using communication channel.

The simplest way to obtain this averaging value is to incorporate all the other units' data into the averaging algorithm at each local controller. However, since this communication algorithm is based on each point-to-point structure, one of the drawback is that there is large amount of data that needs to be transmitted when the network become large and complex. Another aspect should be considered is when the distributed units of Microgrids are dispersedly located, every two units are required to be connected, and this may encounter the limitation of the long distance between them. In this sense, how to simplify the communication algorithm for exchanging data has drawn great attention recently. In the previous literature, the consensus algorithm of multi-agent systems which has a long history in the area of computer science is popularly studied for its application in Microgrids in recent

years [76]. The principle of consensus algorithm is based on obtaining average through just the neighbors of one unit, but not all other components which can efficiently reduce the burden and complexity of the communication link [77].

1.4 MOTIVATION OF THE WORK

The motivation of coordinated control of Microgrids can be originated from the need to control parallel connected converters, which requires that active and reactive power as well as harmonics should be properly distributed among those distributed units according to their power ratings. Based on the specific network configuration that one Microgrid adopted, various power distributed strategies are proposed such as master-slave control [78], [79], average load sharing control [80], [81], circular chain control and droop control [82]. The droop control, which borrows the principle of primary frequency regulation of synchronous generator in large power systems, has drawn great attention in recent years. It was implemented on the control of power electronic converters by adding a virtual inertial to achieve autonomous power regulation without the assistance of external communication link. The early work can be found with Coelho et al. [54], [62], Chandorkar et al. [83], Tuladhar [84], [85] for describing the fundamental working principle, modeling and stability analysis of droop control. Based on those previous work, advanced droop control strategies including the virtual impedance concept [86], [87], reactive power sharing improvement [88], [89], distributed harmonic sharing control [90], [91], active and reactive power decoupled control [92] are then proposed in succession, in order to improve the dynamic and steady state droop control performance.

Although the droop control strategy has withdrawn effective applications such as uninterrupted power supply systems [93] and battery systems [94], its operation principle inherently requires those adopted converters are controlled in VCM. However it still faces limitation when applied on Microgrid with various converters under different control modes to achieve comprehensive power sharing

performance. Especially the Microgrid system with high utilization of renewable energy, the RES units interfaced with power electronic converters are usually controlled in CCM. Despite the organism of proportional power distribution is deeply investigated with VCM units, how to realize a global power sharing performance among both VCM and CCM units are seldom discussed. One recent research that worth noticing for VCM control strategy is proportional-integral (PI) type droop control [95], [96]. It is interesting to observe that the VCM unit with PI droop control is changed to power tracking performance, where conventionally treated as CCM control objective. It indicates that by manipulating the droop slope of primary controller, the VCM unit is able to achieve flexible control performance with respect to frequency/amplitude regulation as well as active/reactive power regulation. In this context, it is worth studying for a coherent primary control that can be symmetrically applied on VCM and CCM units in Microgrids, that the control objectives for both kinds of converters can be flexibly chosen. In this way no matter VCM or CCM units, the primary controlled converters will be treated as equivalent components and operated as black box by receiving the upper level commands for power management.

Another important issue needs to be discussed for the coordination among VCM and CCM units is the way to distributed reactive power. In order to fully utilize the renewable energy at a specific power rating of RES unit, the RES units under CCM control usually deliver no reactive power [97]. Therefore almost all of the reactive power should be supported by the ESS units under VCM. While considering the total output power rating of the converter is fixed, the more reactive power delivered from ESS units, the less active power capacity of ESS used to buffer the unbalance between power generation and consumption is remained. In order to overcome such a limitation, many previous researches have been carried out to investigate the scenario that using RES units to provide reactive power support and improve power quality [97], [98]. However, these methods are based on setting fixed reactive power commands of RES units intensively. And the proportional active and reactive power sharing should be fulfilled by using a microgrid central

controller to adjust the power references of RES units with additional communication link [99]. Thus there is motivation for the study of coordinated control among VCM and CCM units that sharing the reactive power in an autonomous way under droop control principle, as well as taking accounts of the total power rating of each VCM/CCM unit.

As section 1.3.1 indicates, the coordinated active power control strategy should consider the statuses of all microgrid elements such as the SoC of ESS, power available from the RES, and demand of power consumption. Since the ESS plays an important role for achieving the goal of power balance and grid frequency support, the capability of ESS to regulate power among DG units is a key index for the coordinated control. In order to keep the SoC of ESS in a safe region when perform power regulation, several methods for prediction and optimal sizing of ESS are thereby developed [100], [101]. However, the ESS needs to be redesigned when the total energy generation/consumption is changed. Model predictive control based coordinated control strategy is proposed for the power management among DG and ESS units according to different Microgrid operation modes [70], [99]. Meanwhile previous work presented in [94] and [102] develop coordinated SoC control strategy with microgrids management systems to keep the Microgrid frequency/voltage stable. Other similar approaches can be found in [103] to achieve demand side control with assistance EMS in the applications of Microgrids. The common distinct of these studies is that the coordinated performance of Microgrids depending on central controller.

PLC method has attracted much attention recently for its coordinated performance in distributed level. However, these methods intensively introduce a series of high frequency noise to the power cables and the selection of the resonant frequencies for transmission is hard to be designed to avoid overlapping [104], [105]. The applications of BSM studies can be seen in [69], [106], [107] which employs bus voltage levels as communication signals in DC Microgrids. Based on the bus voltage signals, ESS and RES units change output power or operation modes according to these researches. Nevertheless seldom studies have been found

with this kind of BSM in the AC Microgrid applications and few of them discuss the full scenario considering both power generation and demand side response.

Those aforementioned approaches are focused on coordinated control in primary level. Even though the coordinated performance can be achieved in a distributed way, the higher level control paradigm can lay an influence on its decentralization. Hereby distributed secondary control, due to its better robustness and easier scalability has raised great attention in recent years in Microgrid applications [108], [109]. Especially the consensus algorithm based distributed system worth noticing for its simpler communication configuration. And related researches can be found in such as [110]–[112] for its application in AC Microgrids, in terms of bus voltage/frequency restoration [108], [111], and accurate reactive power sharing [113]. Similar research outcome for bus voltage restoration in DC Microgrids which address the limitation of line impedance variation can be look into [110], [114]. Nevertheless all the verification among those studies are based on droop control strategies and have not taken into account the significant difference of inner loop control modes among Microgrid components.

1.5 THESIS CONTRIBUTION

In order to achieve a coherent decentralized power distribution among VCM and CCM units as discussed in previous section, this thesis proposes a flexible primary level including both droop and reverse droop control strategies. The symmetrical characteristic of inner loop and primary loop of VCM and CCM units are analyzed and compared, which indicates that by proper designing the slopes of primary controller, the control objectives including voltage/frequency regulation, active/reactive power control can be actively exchanged between VCM and CCM units. In this way the global autonomous power distribution method including all VCM and CCM units is thereby derived.

Furthermore, adaptive reactive power sharing control strategy is implemented based on this coherent primary level which takes into account the total power rating

limitation of each unit. In this way for both VCM and CCM units the reactive power distribution is not independently controlled, but adaptively adjusted based on the active power regulation inside Microgrids.

In order to address the challenge as mentioned in previous section for developing such a distributed coordinated performance considering the prime source conditions, two BSM methods are proposed in this thesis: (i) smooth switching droop control (SSDC) which is based on manipulating the droop slopes of distributed units depending on the SoC conditions of ESS, bus frequency thresholds as well as the power availability from RES. In this context, different operation modes according to the distributed units' conditions are defined. And hereby the seamless modes transferring procedure is required. (ii) distributed coordinated control based on grid frequency controller and active power controller is proposed. In a further step, those two controllers are implemented on the top of the conventional VCM and CCM inner loops respectively, without altering the inner loop control objective as a result. The advantage taken by this method is that no control modes transferring action is needed during the coordination procedure.

This thesis also investigated the BSM based distributed coordinated control in DC islanded Microgrids that takes into account both power regulation from both generation side and demand side response. For both AC and DC islanded Microgrids, the BSM based distributed control is able to achieve power distribution according to different operational scenarios of Microgrids in an autonomous way without the higher level interference, so the robustness and simplicity of overall system has been improved. This improved performance of the proposed distributed conventional centralized coordinated control is also compared in this study.

Finally in order to toward more decentralization of the overall islanded Microgrids, consensus algorithm based secondary control is implemented together with distributed coordinated control. The dynamic consensus method is utilized in secondary level to avoid the out-of-synchronization of secondary action which may deteriorate the coordinated performance. In this way, the hierarchical coordinated control can be decentralized not only in primary level but throughout hierarchical

level, which adopts only a sparse communication network spanned across microgrid. Additionally, the weight calculation procedure for optimal converging speed is also presented, so that the overall system can find out converged secondary control variables in a fast way.

1.6 THESIS OBJECTIVES

The objectives of this thesis are mainly focused on:

- To give the review of previous researches on coordinated control strategies on both AC and DC islanded Microgrids. Especially to study the distributed coordinated control based on BSM implementation for Microgrids.
- To develop a generalized primary level not only based on droop method but also include reverse droop control that takes into account the inherent difference of VCM and CCM units. Meanwhile to further study the symmetrical characteristic and their relationship of inner loop and primary loop controllers of VCM and CCM units.
- Based on generalized primary control level, this thesis also aims to develop adaptive reactive power sharing method which depends on the active power distribution status of Microgrids. The thesis targets to incorporate this approach into the droop and reverse droop control strategies with autonomous reactive power sharing.
- To develop the BSM-based coordinated control for both AC and DC islanded Microgrids, which taking into account the prime source conditions of distributed units, based on two methods in this thesis: (i) SSDC and (ii) active regulation of grid frequency/voltage control. Those two approaches can be classified into passive and active BSM methods respectively.
- To further develop the decentralized hierarchical coordinated control with both primary and secondary level. This thesis aims to adopt

the consensus algorithm in the distributed secondary control level for its simplification of the communication configurations.

1.7 THESIS OUTLINE

This thesis is organized into seven chapters as following:

Chapter 2 presents the first paper published in a conference which introduced an autonomous active and reactive power distribution strategy that can be applied directly on CCM converters, being compatible as well with conventional droop-controlled VCM converters. Since different DG units contribute various active power, the proposed reactive power distribution is adaptively controlled according to the active power distribution in islanded Microgrids. Finally, the virtual impedance is implemented in this paper for the improvement of the reactive power sharing.

Chapter 3 presents a journal paper published in IEEE Transactions on Smart Grid. In this paper, a coordinated architecture of islanded AC microgrids with SSDC is derived. The proposed approach allows a flexible power regulation and bus voltage/frequency regulation of each distributed unit based on seamless modes changes. And this manner of decentralized power management can be achieved by BSM approach. The power management policy based on different operational modes is explained in details. In addition, small-signal analysis is carried out for the study of parameters' impact on system stability and transient response. Real-time simulations are carried out to provide different operational scenarios of AC islanded Microgrids.

Chapter 4 presents a journal paper published in IEEE Transactions on Energy Conversion. In this paper, an autonomous active power control to coordinate distributed components of AC islanded microgrid consisting of the ESS, the PV systems and loads is proposed. Compared to the SSDC this coordinated control does not require any modes switching actions. And the implementation of grid-frequency-control, and active-power-control which compatible with conventional

CCM converter integrated with MPPT functions are detailed explained. Furthermore, the hierarchical coordinated control based on a simple centralized secondary controller is presented. In this way, distinct coordinated functions are assigned with the primary and secondary layers of Microgrids.

Chapter 5 presents a journal paper published in IEEE Transactions on Smart Grid, where the distributed coordinated control strategy is implemented in DC islanded Microgrids. Both generation side control and demand side management are discussed in this paper. And comparison of proposed distributed coordinated control with previous centralized coordinated control is studied by discussing the scenarios that communication fails and dynamic response when the coordination signals set to be activated.

Chapter 6 presents the work published in a conference paper. In this paper, a decentralized secondary control is implemented in order to eliminate the frequency changes caused by the primary coordinated control, so that the decentralized hierarchical coordinated performance is achieved. By using the consensus algorithm method, the limitation that all decentralized secondary controllers must be mutually synchronized can be addressed. Moreover, the dynamic consensus algorithm is also introduced in order to fit the time-variant data transmitting topology of secondary level. The hierarchical control algorithm implemented in an islanded AC microgrid system is tested in different scenarios by means of real-time simulation.

Chapter 7 discusses the conclusions of this thesis, highlights the contributions and introduces the future work brought along the thesis.

CHAPTER 2 PAPER 1

Autonomous Active and Reactive Power Distribution Strategy in Islanded Microgrids

D. Wu, F. Tang, J. M. Guerrero, J. C. Vasquez, G. Chen, and L. Sun

The paper has been published in
Proceeding of 2014 IEEE Applied Power Electronics Conference and Exposition
(APEC 2014), pp. 2126–2131, 2014.

CHAPTER 3 PAPER 2

A Control Architecture to Coordinate Renewable Energy Sources and Energy Storage Systems in Islanded Microgrids

D. Wu, F. Tang, T. Dragicevic, J. C. Vasquez, and J. M. Guerrero

The paper has been published in
IEEE Transactions on Smart Grid, vol. 6, no. 3, pp. 1156–1166, May 2015.

CHAPTER 4 PAPER 3

Autonomous Active Power Control for Islanded AC Microgrids With Photovoltaic Generation and Energy Storage System

D. Wu, F. Tang, T. Dragicevic, J. C. Vasquez, and J. M. Guerrero

The paper has been published in
IEEE Transactions on Energy Conversions, vol. 29, no. 4, pp. 882–892, Dec. 2014.

CHAPTER 5 PAPER 4

Coordinated Control Based on Bus-Signaling and Virtual Inertia for Islanded DC Microgrids

D. Wu, F. Tang, T. Dragicevic, J. M. Guerrero, and J. C. Vasquez

This paper has been published in
IEEE Transactions on Smart Grid, vol. PP, no. 99, pp. 1–1, 2015.

CHAPTER 6 PAPER 5

Secondary Coordinated Control of Islanded Microgrids Based on Consensus Algorithms

D. Wu, T. Dragicevic, J. C. Vasquez, J. M. Guerrero, and Y. Guan

This paper has been published in
Proceeding of 2014 IEEE Energy Conversion Congress and Exposition (ECCE),
2014, pp. 4290–4297.

CHAPTER 7

CONCLUDING REMARKS

The final chapter of this thesis presents the conclusions developed in this study of coordinated control of islanded Microgrids. This chapter includes the highlights of approach novelty proposed in this research, and also the corresponding future work which can be extended as continue studies within the related topics.

7.1 SUMMARY

This thesis focuses on the coordinated control strategies for both AC and DC islanded Microgrids, especially the distributed approaches in order to enhance the system scalability and reliability. The thesis begins with reviewing the hierarchical structure of Microgrids, which introduces the various functionalities assigned in each level. With primary and secondary control strategies, it establishes a bridge among distributed components with physical link and communication link respectively. In this context, this thesis is mainly focused on the exploit for the coordinated performance of the Microgrid elements by the usage of these two links.

Firstly the inherent difference of control principle and performance of VCM and CCM are detailed investigated. It shows that the distinct difference of inner loop regulation leads to the need for more comprehensive primary loop control strategies that can be adopted for both the VCM and CCM units to support grid and distribute power at the meantime. This study was presented in Chapter 2 where a conference paper is published. Additionally in this study an adaptive reactive power distribution method is introduced in primary level control for all VCM and CCM units, where the reactive power can be real-time redistributed in terms of the active power regulation.

In order to achieve coordinated performance among RES and ESS with CCM and VCM control modes taking into account the prime source conditions, a control

architecture was proposed in Chapter 3. In this study, SSDC was implemented for each ESS and RES unit which adjusts droop slopes to switch modes. Meanwhile, four operational modes and decentralized modes transition of system can be defined. The coordinated control implementation was illustrated and small-signal analysis was carried out based on the proposed control strategies.

In a further investigation, a BSM method that does not need any mode changing actions is proposed for the coordination between RES and ESS units, and this work for AC islanded Microgrids has been discussed in Chapter 4. By the proposed active power control, SoC of the ESS can be kept within the safe limits by automatically adjusting the power generation from the PV systems and load consumption. This coordination performance was obtained by using only local controllers and does not rely on external communication links. Then a centralized secondary controller is implemented to achieve bus frequency restoration that performed as an auxiliary function. The implementation of this BSM based coordinated control for DC islanded Microgrids application is presented in Chapter 5 that utilizing DC bus voltage thresholds as a carrier to inform power conditions of different distributed units, together with various real-time testing scenarios for the comparison study of dynamic and steady state performance between the proposed and conventional approaches.

Those aforementioned studies were focused on primary level control that utilizing power line link to coordinate distributed units. Finally, distributed secondary control that compatible with the primary coordinated control was discussed in Chapter 6. This distributed secondary control utilized consensus algorithm in order to promote the further decentralization of the overall system. In this work, the scientific steps for developing fast iteration process were derived. In addition dynamic consensus algorithm was implemented to overcome the asynchronization problem among the distributed units and limitation that conventional consensus algorithm cannot deal with the time-variant data transmitting in this secondary control level.

All these proposed control strategies were tested and verified by using setups in Intelligent Microgrid Laboratory (iMGL) at Department of Energy Technology, Aalborg University. The proposed studies were constructed by Matlab/Simulink environment and implemented in dSPACE 1006 real-time simulation platform.

7.2 CONTRIBUTIONS

The concrete contributions of this thesis are highlighted as following:

- Development of coherent primary level control that is compatible with both VCM and CCM units, in order to achieve global active and reactive power distribution approach. Adaptive reactive power control was proposed together with droop and reverse droop control strategies.
- Development of distributed coordinated control strategies based on BSM that employed only power line as communication channel to obtain fundamental coordinated performance that ensured the system robust performance. The SSDC approach is firstly investigated with applying P and PI droop controllers to manipulate the droop slopes according to difference control modes of Microgrid operation.
- Development of distributed coordinated control strategies that integrate both generation control and demand side management. Based on the proposed method, no control modes switching actions is required and therefore a smooth system operation can be obtained when SoC approaches to limitation. This method was implemented in both AC and DC islanded Microgrids.
- Development hierarchical coordinated method with applying consensus algorithm in secondary level toward a more decentralized control structure. In this work, not only the fundamental coordinated performance can be obtained in a distributed way, the auxiliary coordinated performance like the frequency restoration can be realized in a total decentralized manner.

Detailed deriving steps for the decentralized system construction and coefficients for iteration steps were given.

7.3 FUTURE WORK

The methods and contributions that developed in this thesis show the following promising aspects that can be investigated in the future:

- Distributed coordinated control considering harmonics distribution: further investigation of the dual characteristics of VCM and CCM units for the harmonic voltage/current control. Hereby construct a more comprehensive primary level that is able to incorporate the harmonic distribution method generally applied on VCM and CCM units.
- Coordinated control strategies of Microgrids when the islanded mode operation switched to grid-connected operation: further investigation can be carried out to see how the BSM-based distributed method influences on grid-connected mode operation.
- Advanced consensus algorithm based hierarchical control strategies: With BSM method brought along in this thesis, fundamental coordinated control objectives can be realized in primary level, while consensus-algorithm-based system using communication link shows an alternative way to coordinate all the distributed units. Therefore it worths investigating which way shows the best promising solution as BSM method or consensus algorithm method for the coordination performance.
- Long term coordinated control objectives together with distributed coordinated approach developed in this paper: For example the coordinated control can incorporate power prediction, energy generation/consumption taking into account the market revenue. Thus, the interactive effect between those basic coordinated functions and advanced coordinated functions can be analyzed.

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